

Scalable Solution using PETSc for Multiple Time-scale Electrical Power Grid Dynamics Simulation

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- What is PETSc?

- Numerical library for developing large-scale parallel applications (mostly PDE)
- Free for anyone to use including industrial users
- Support via petsc-maint@mcs.anl.gov
- Hyperlinked documentation and hundreds of tutorial style examples.
- Began in Sep. 1991 as a platform for experimentation.

- Portability

- Unix, Linux, MacOS, Windows
- Tightly/loosely coupled architectures
- 32/64 bit ints, real/complex, single/double/quad precision

- Extensibility

- BLAS, LAPACK, BLACS, Scalapack
- ParMetis, Jostle, Party
- SuperLU, MUMPS, UMFPack
- Prometheus, HYPRE, ML, SPAI
- SunDials

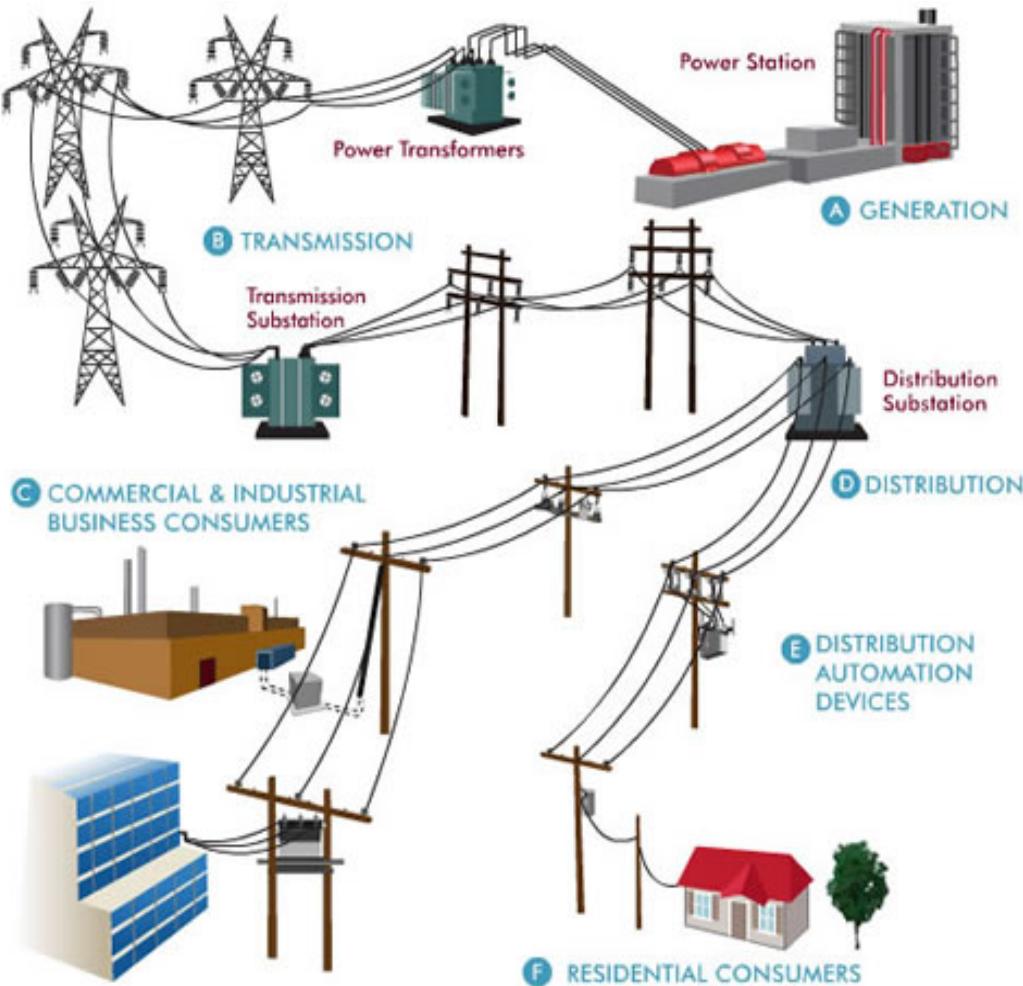
- Toolkit

- Parallel vectors, matrices
- Krylov subspace based linear solvers
- Serial and parallel preconditioners
- Nonlinear solvers, ODE/DAE integrators
- Interface to third-party solvers
- Flexible runtime options
- Debugging and profiling

Multiscale simulation

- Simulate phenomenon over different spatial and temporal scales
 - Different physics having disparate time-scales
 - Coarse and detailed models
 - Local and global regions.
- Few application areas
 - Biology
 - Meteorology
 - Material science
 - Electrical power grid

Electrical Power Grid



Different Physics

- Mechanical generators and motors
- Electrical transmission lines, transformers
- Electrical and mechanical loads.
- Power electronics equipment .

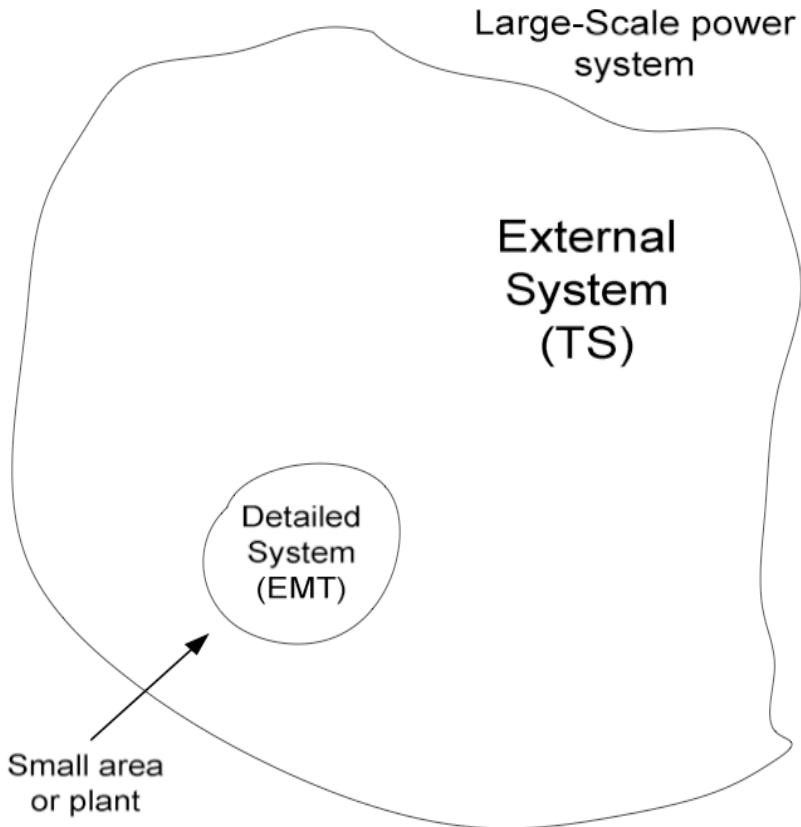
Types of disturbances and time-scales

Phenomenon	Timescale
Lightning propagation	Microseconds to milliseconds
Switching surges	Microseconds to tens of seconds
Electrical transients	Milliseconds to seconds
Electromechanical transients	Hundredths to tens of seconds
Mechanical transients	Tenths of seconds to hundreds of seconds
Boiler and long term dynamics	seconds to thousands of seconds

- Existing analysis tools developed for a specific time-scale of interest
 - Transient Stability Simulators (TS)
 - Milliseconds to minutes time frame
 - Can capture only fundamental frequency harmonics
 - Electromagnetic transients simulators (EMT)
 - Microseconds to seconds time frame
 - Can capture harmonics over a larger frequency spectrum

Multiple time-scale electrical power grid simulation

- Divide the network into a smaller EMT region and larger TS region



Interface required over space,
time, and waveform due to

Property	TS	EMT
Time step	On the order of milliseconds	On the order of microseconds
Network Modeling	Balanced positive sequence	Three phase unbalanced
Voltages and currents	Phasor	Instantaneous

Equations for TS and EMT

- Nonlinear Equations for TS and EMT

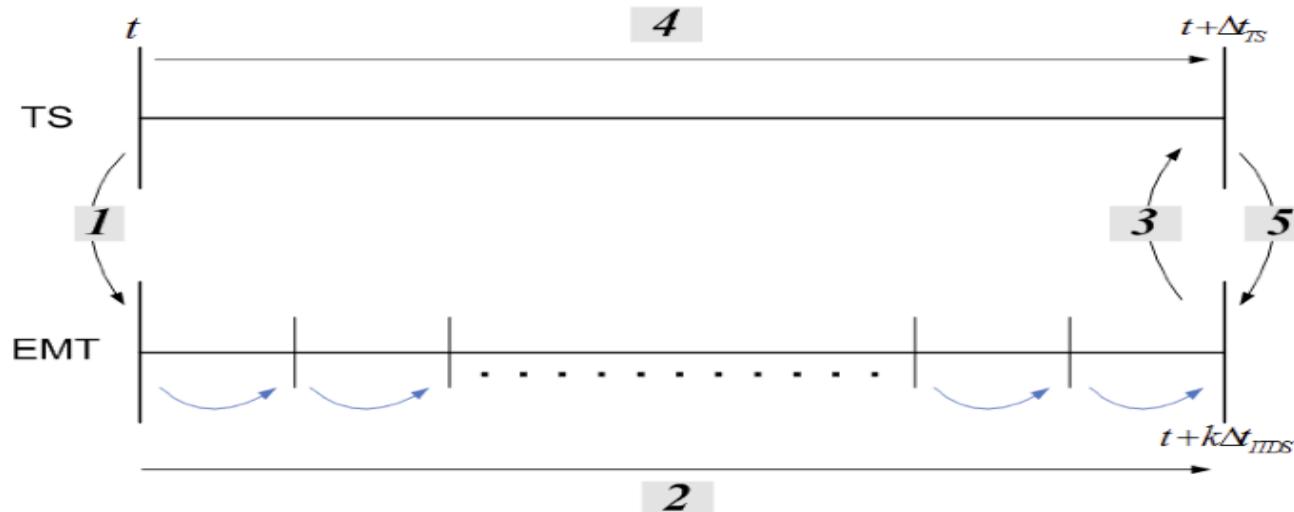
$$\begin{aligned}\frac{dX_{TS}}{dt} &= F(X_{TS}, V_{TS}) \\ 0 &= G(X_{TS}, V_{TS}, I_{BDRY})\end{aligned}$$
$$\begin{aligned}\frac{dx_{EMT}}{dt} &= f_1(x_{EMT}, i_{bdry}) \\ \frac{di_{bdry}}{dt} &= f_2(x_{EMT}, i_{bdry}, v_{thev})\end{aligned}$$

TS

EMT

- TS uses timestep in the order of milliseconds
- EMT uses timestep in the order of microseconds

Existing “Explicit” interaction protocol



- ① Pass data back and forth between TS and EMT at each TS time step.
- ② Faces convergence issues when having large changes at consecutive time boundaries.
- ③ Limited parallelism
 - ① TS idle when EMT is running and vice-versa
 - ② EMT network is very small compared to TS network.

Implicitly coupled solution approach (TSEMT)

- Equations for each TS and EMT time step

$$\begin{aligned}\frac{dX_{TS}}{dt} &= F(X_{TS}, V_{TS}) \\ 0 &= G(X_{TS}, V_{TS}, I_{BDRY})\end{aligned}$$
$$\begin{aligned}\frac{dx_{EMT}}{dt} &= f_1(x_{EMT}, i_{bdry}) \\ \frac{di_{bdry}}{dt} &= f_2(x_{EMT}, i_{bdry}, v_{thev})\end{aligned}$$

TS

EMT

- Approach : Solve TS and coupled-in-time EMT equations simultaneously at each TS time step

TSEMT equations for each TS time step

Coupled-in-time EMT equations

TS equations

$$\text{TS3ph} \left\{ \begin{array}{l} X_{TS}(t_{N+1}) - X_{TS}(t_N) - \frac{\Delta t_{TS}}{2} (F(X_{TS}(t_{N+1}), V_{TS}(t_{N+1})) + \\ F(X_{TS}(t_N), V_{TS}(t_N))) = 0 \\ G(X_{TS}(t_{N+1}), V_{TS}(t_{N+1}), I_{BDRY}(t_{N+1})) = 0 \end{array} \right.$$

$$\text{EMT} \left\{ \begin{array}{l} x_{EMT}(t_{n+1}) - \frac{\Delta t_{EMT}}{2} f_1(x_{EMT}(t_{n+1}), i_{bdry}(t_{n+1})) \\ - x_{EMT}(t_n) - \frac{\Delta t_{EMT}}{2} f_1(x_{EMT}(t_n), i_{bdry}(t_n)) = 0 \\ i_{bdry}(t_{n+1}) - \frac{\Delta t_{EMT}}{2} f_2(x_{EMT}(t_{n+1}), i_{bdry}(t_{n+1}), v_{thev}(t_{n+1})) \\ - i_{bdry}(t_n) - \frac{\Delta t_{EMT}}{2} f_2(x_{EMT}(t_n), i_{bdry}(t_n), v_{thev}(t_n)) = 0 \\ x_{EMT}(t_{n+2}) - \frac{\Delta t_{EMT}}{2} f_1(x_{EMT}(t_{n+2}), i_{bdry}(t_{n+2})) \\ - x_{EMT}(t_{n+1}) - \frac{\Delta t_{EMT}}{2} f_1(x_{EMT}(t_{n+1}), i_{bdry}(t_{n+1})) = 0 \\ i_{bdry}(t_{n+2}) - \frac{\Delta t_{EMT}}{2} f_2(x_{EMT}(t_{n+2}), i_{bdry}(t_{n+2}), v_{thev}(t_{n+2})) \\ - i_{bdry}(t_{n+1}) - \frac{\Delta t_{EMT}}{2} f_2(x_{EMT}(t_{n+1}), i_{bdry}(t_{n+1}), v_{thev}(t_{n+1})) \\ = 0 \\ \vdots \\ \vdots \\ i_{bdry}(t_{n+k}) - \frac{\Delta t_{EMT}}{2} f_2(x_{EMT}(t_{n+k}), i_{bdry}(t_{n+k}), v_{thev}(t_{n+k})) \\ - i_{bdry}(t_{n+k-1}) - \frac{\Delta t_{EMT}}{2} f_2(x_{EMT}(t_{n+k-1}), \\ i_{bdry}(t_{n+k-1}), v_{thev}(t_{n+k-1})) = 0 \end{array} \right.$$

(6.12)

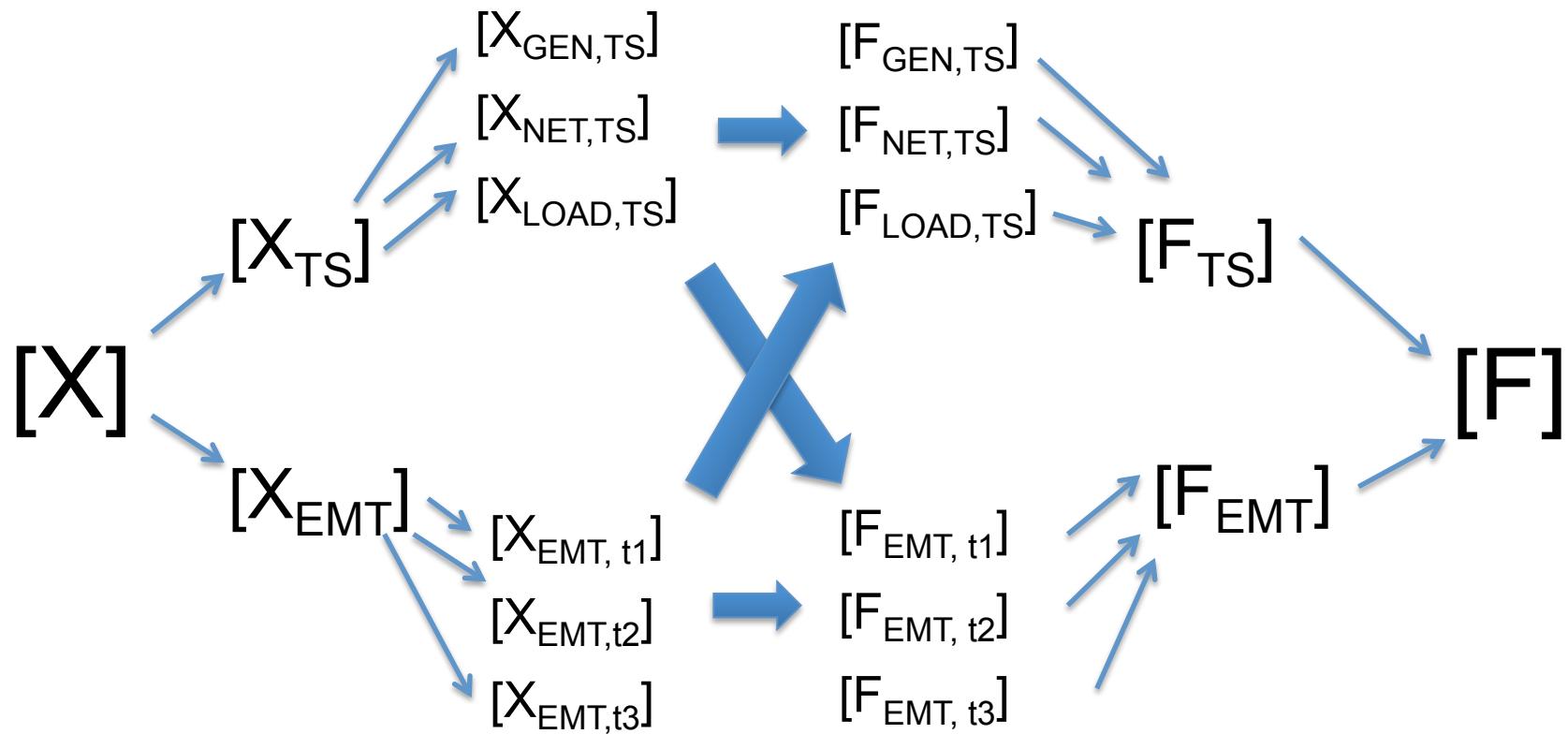
Dimensions of an example TSEMT problem

- External system (TS) : 1000 nodes, 2000 lines, 1000 loads, and 300 generators
- Detailed system (EMT): 3 nodes, 2 lines, 3 loads.
- 1 TS time step = 100 EMT time steps
- TS variables for each time step: 8700
- EMT variables for each EMT time step: 30
- EMT variables for 100 EMT time steps : 3000
- Size of the system to be solved : $8700 + 3000 = 11700$

- Parallel TSEMT
 - Uses spatial decomposition for the TS part and temporal decomposition for the EMT part.
 - The external system is bigger than the detailed system.
 - Coupled-in-time EMT equations need to be solved together.
 - Communication for time-coupled EMT equations is less if the equations are partitioned in time.

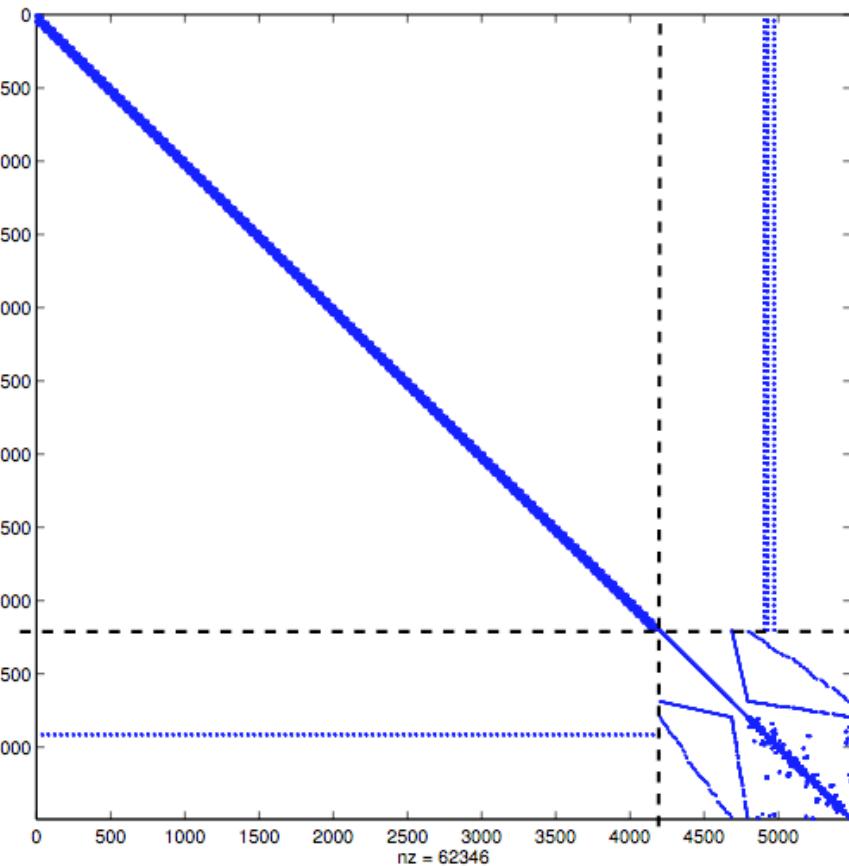
TSEMT code management

- Packing and unpacking of solution and residual vectors via **VecPlaceArray()** at each time step



PETSc's Fieldsplit preconditioning

TSEMT Jacobian



Block-Jacobi or additive

$$\begin{bmatrix} J_{EMT,EMT}^{-1} \\ J_{TS,TS}^{-1} \end{bmatrix}$$



Block-Gauss-Siedel or Multiplicative

$$\begin{bmatrix} I & & \\ & J_{TS,TS}^{-1} & \end{bmatrix} \begin{bmatrix} I & \\ -J_{EMT,TS} & I \end{bmatrix} \begin{bmatrix} J_{EMT,EMT}^{-1} & \\ & I \end{bmatrix}$$

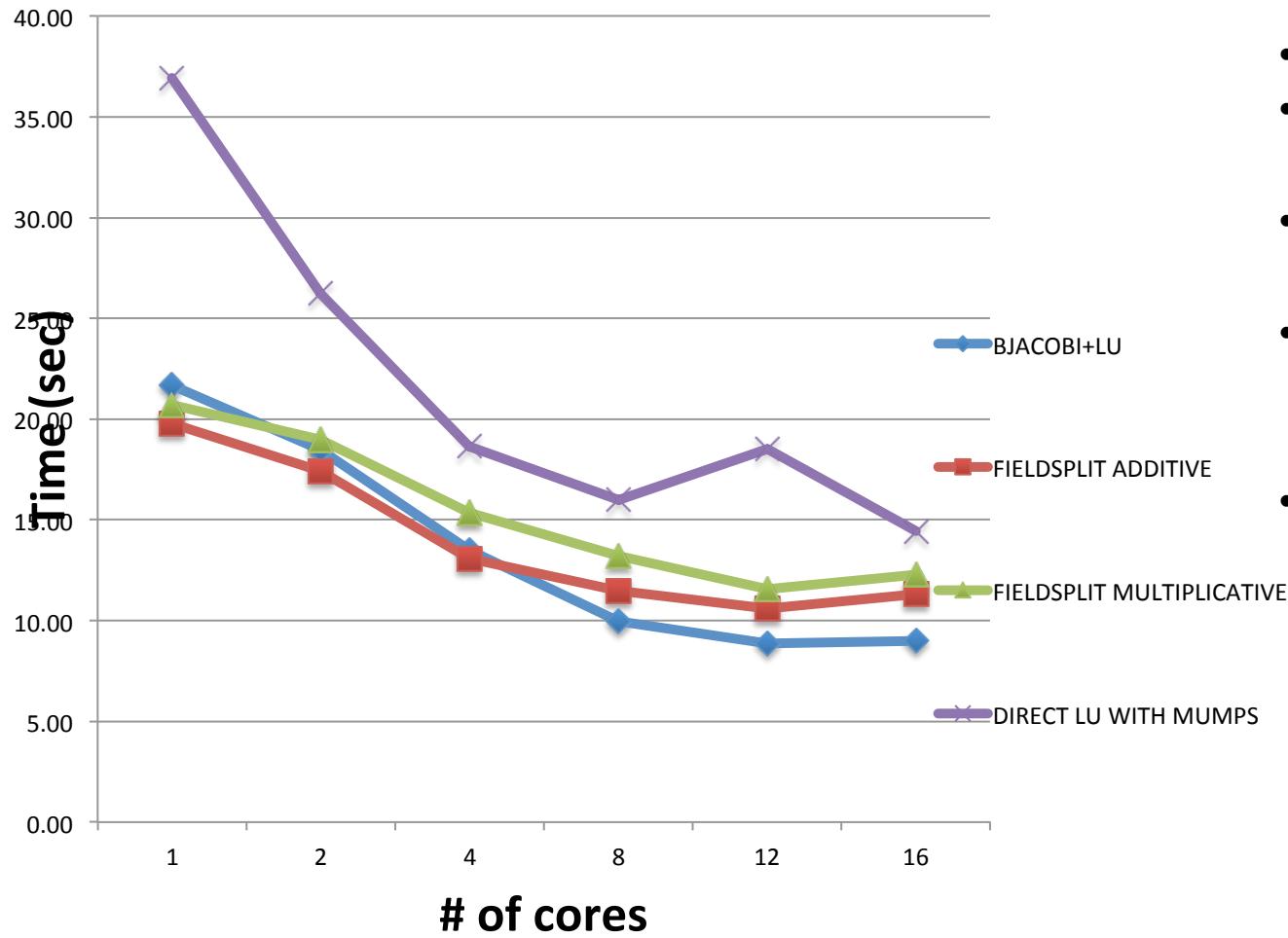


Schur-complement based

$$\begin{bmatrix} I & -J_{EMT,EMT}^{-1} J_{EMT,TS} & \\ & I & \end{bmatrix} \begin{bmatrix} J_{EMT,EMT}^{-1} & \\ & S^{-1} \end{bmatrix} \begin{bmatrix} I & \\ J_{TS,EMT} J_{EMT,EMT}^{-1} & I \end{bmatrix}$$

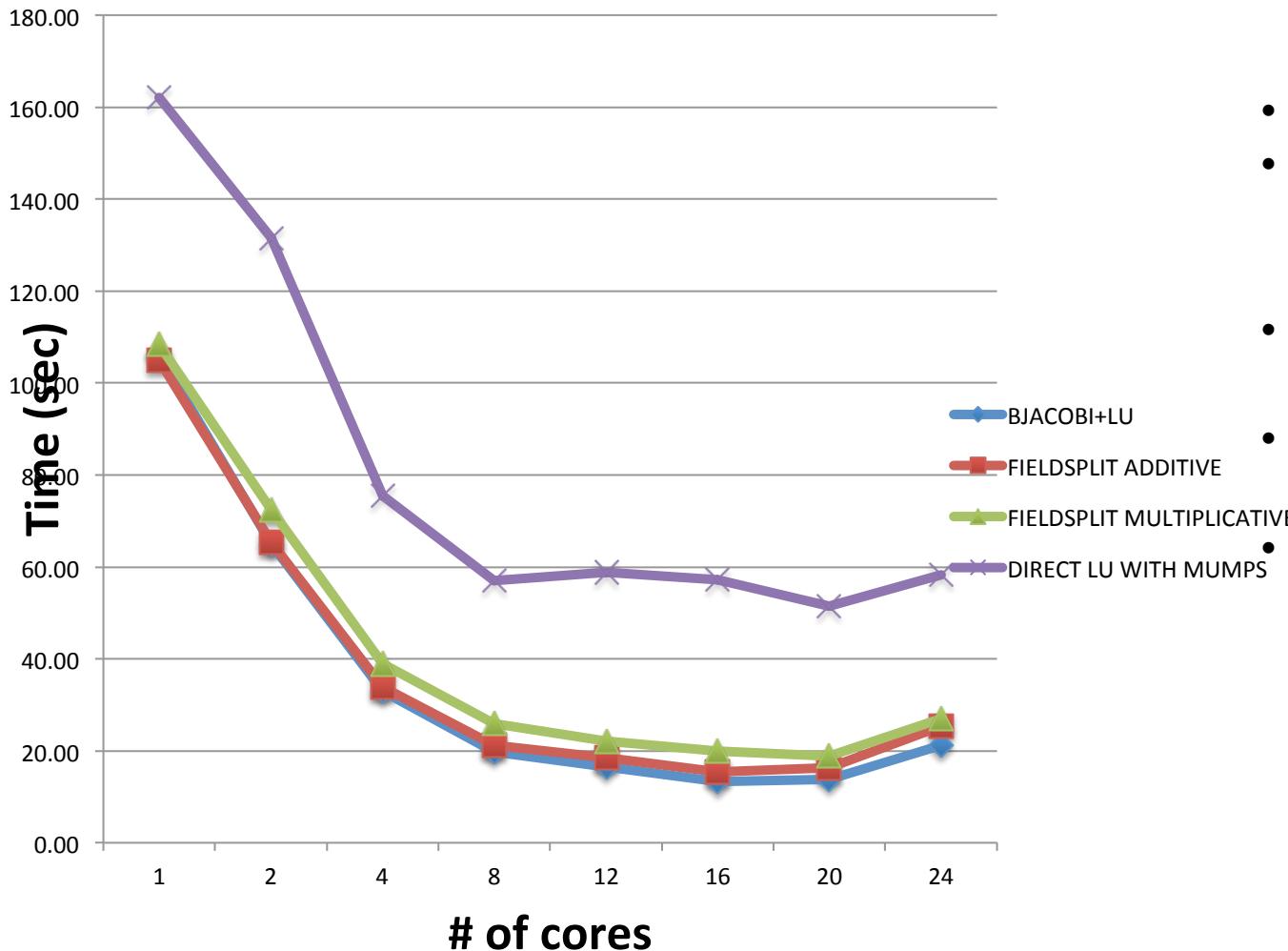
where $S = J_{TS,TS} - J_{TS,EMT} J_{EMT,EMT}^{-1} J_{EMT,TS}$

Parallel TSEMT performance results



- 3 second simulation.
- TS time step = 0.01667 sec.
- EMT time step = 0.0001667 sec.
- TS ~ 10000 variables each time step.
- EMT ~ 36 variables each time step.

Parallel TSEMT performance results (cont.)

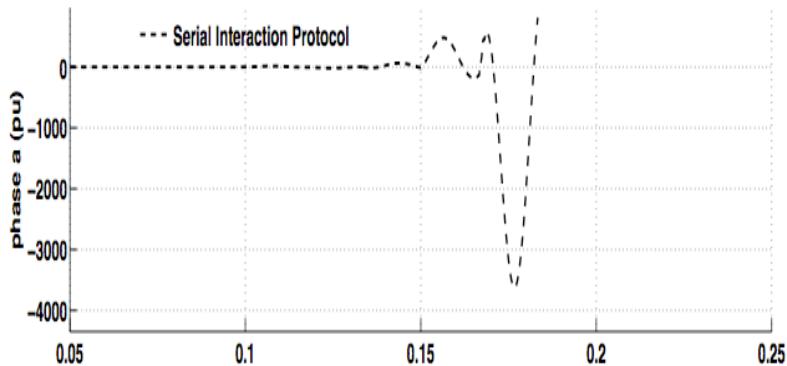
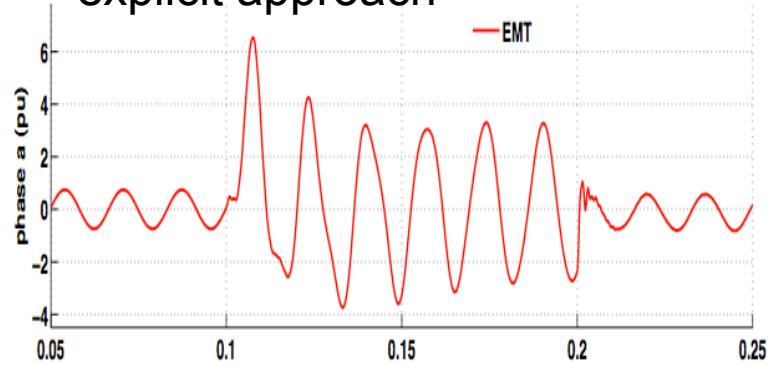


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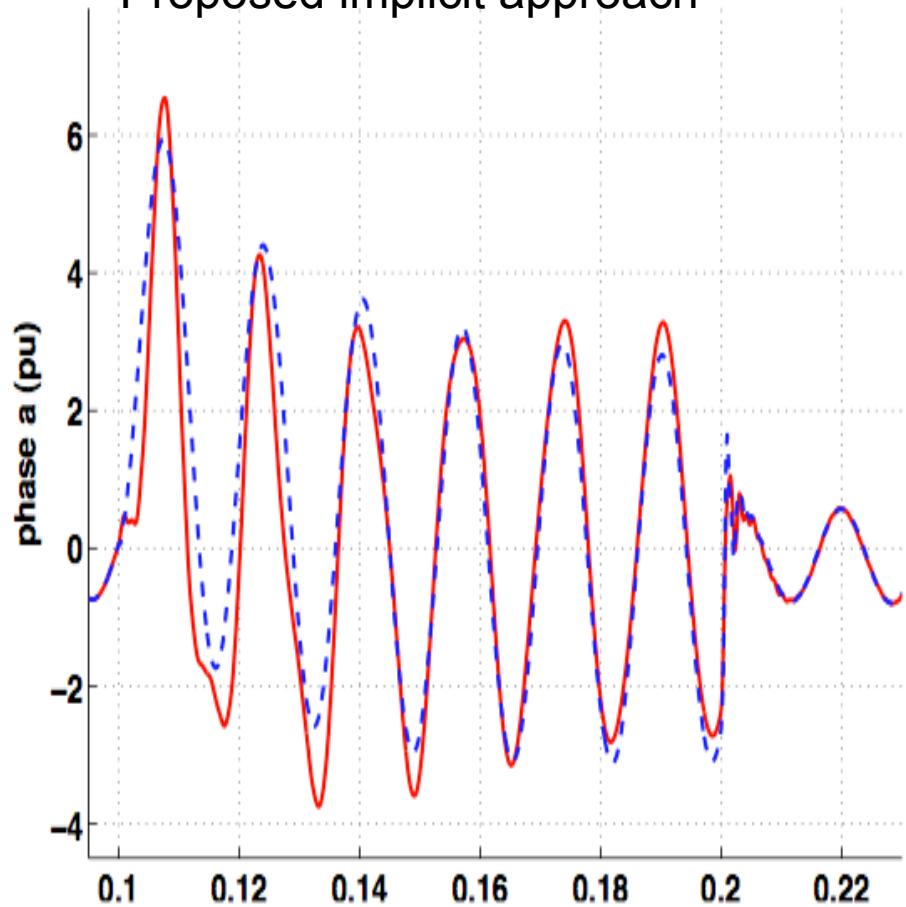
QUESTIONS?

Comparison of explicit and implicit approach

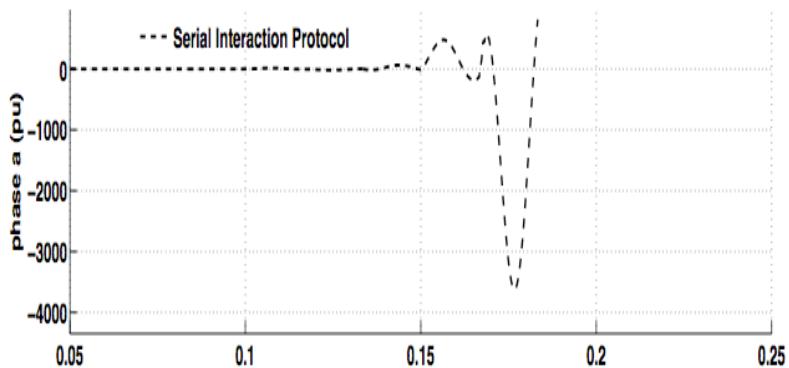
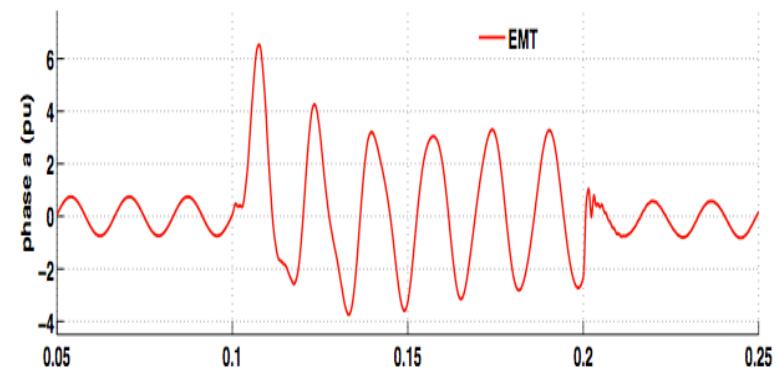
True EMT result and existing explicit approach



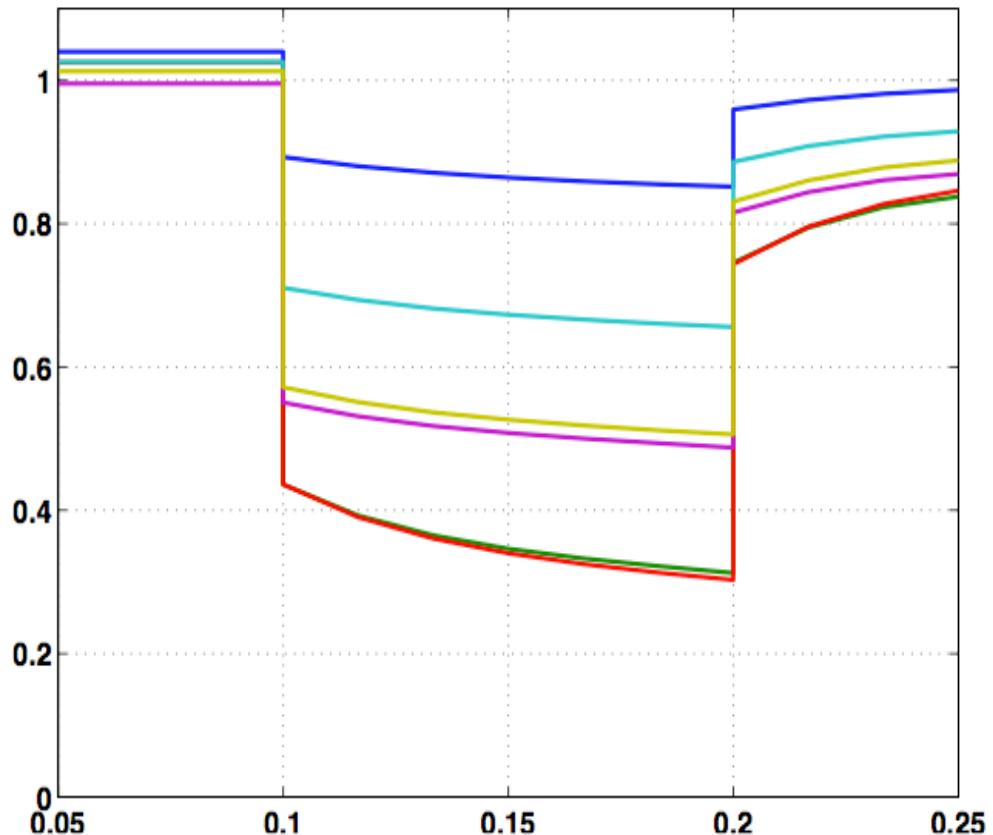
Proposed implicit approach



Existing “Explicit approach – Fails for large changes



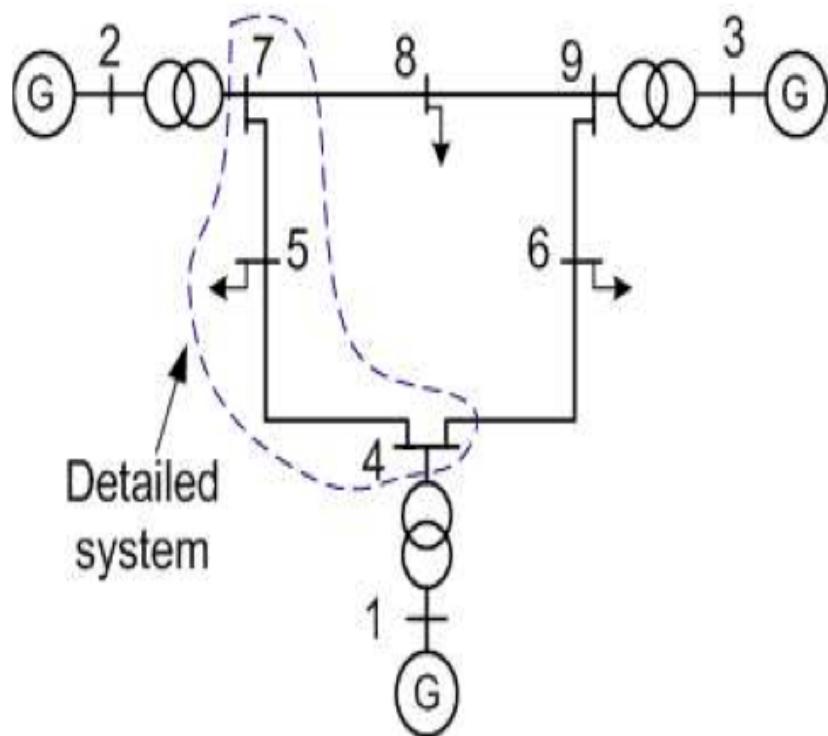
Bus 7 phase a boundary current



Voltage profile of external system

TS3ph-TSEMT simulation results

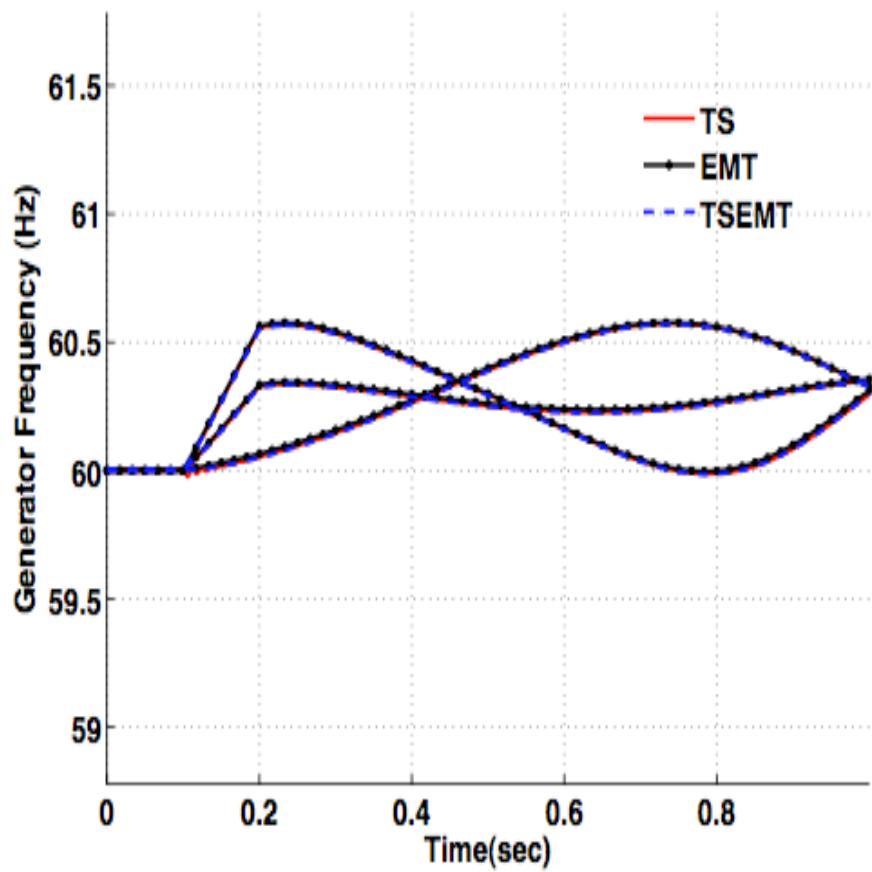
- WECC 9-bus system



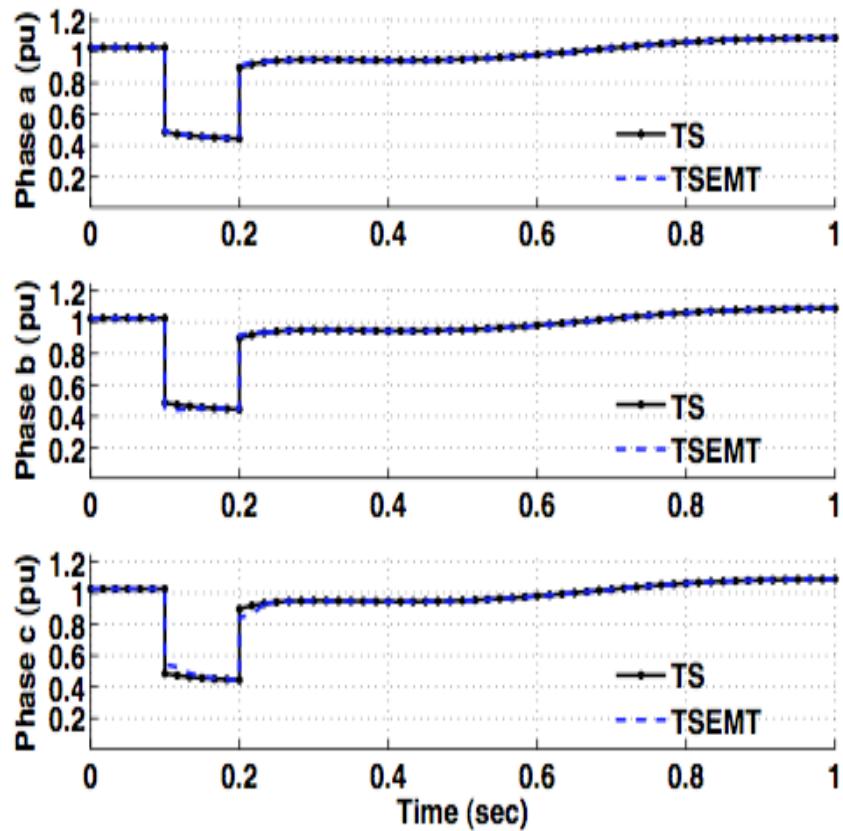
- Disturbance scenario:
 - Three phase fault on bus 5 at 0.1 seconds and clearing time varied.
- Total simulation time = 1 second
- TS3ph time step = 0.01667 second
- EMT time step = 0.0001667 second
- TS3ph runs initially until 0.05 seconds.
- Network is split and TSEMT commences till merging algorithm detects that boundary bus voltages are close enough to terminate TSEMT.
- On TSEMT termination, TS3ph continues until simulation end time

Fault cleared at 0.2 seconds (external system slow dynamics)

Generator frequencies



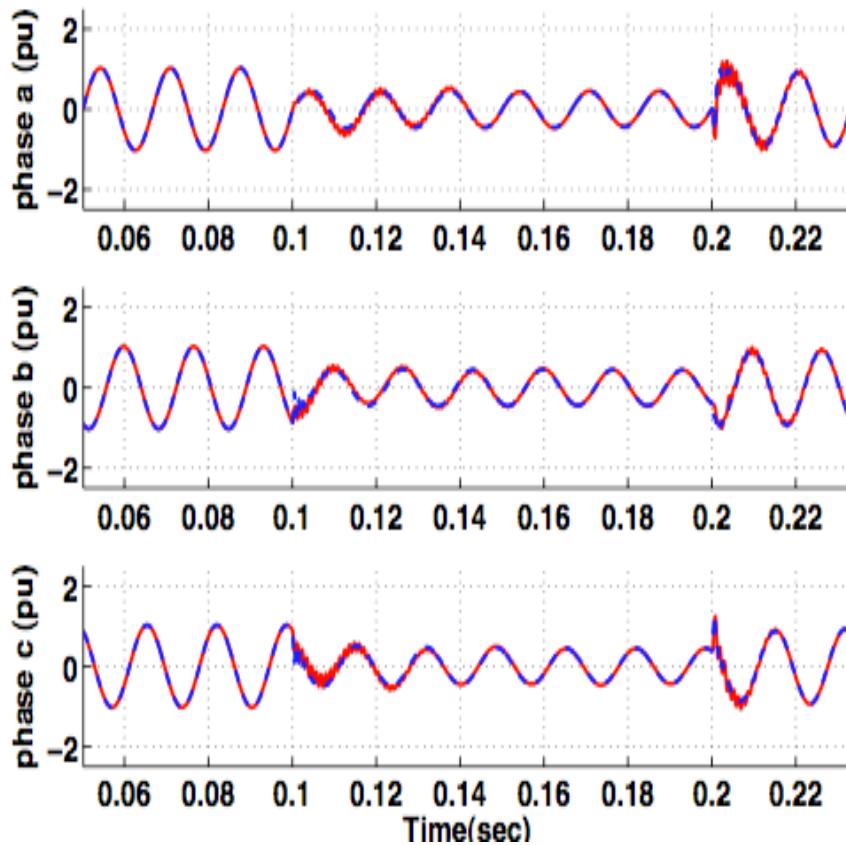
Bus 4 voltage magnitudes



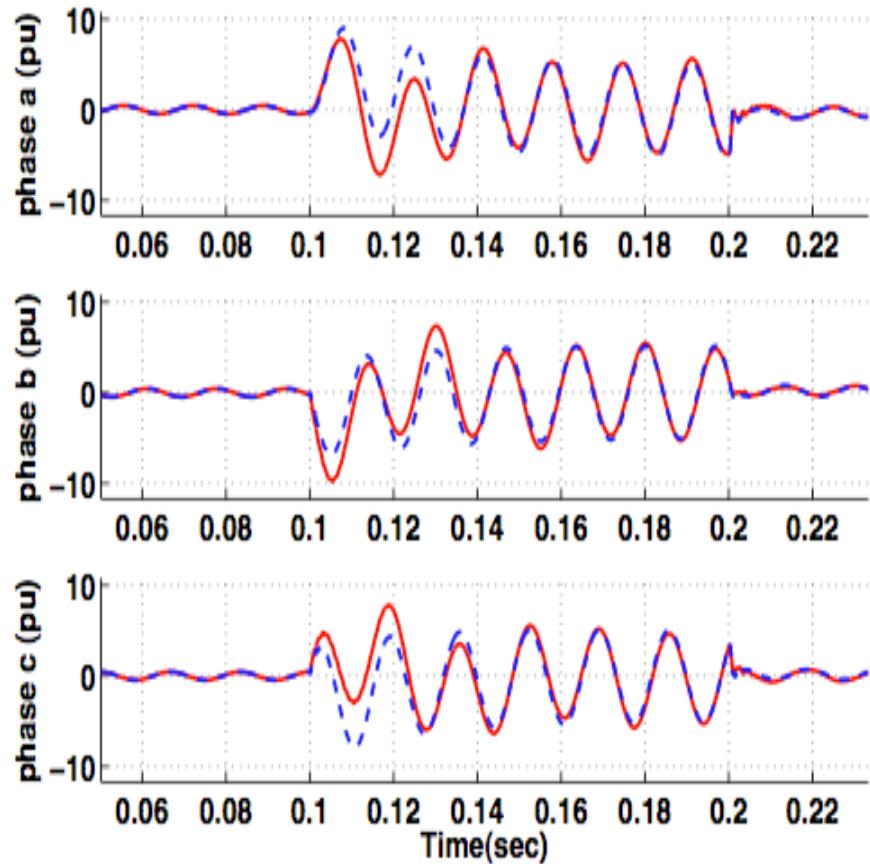
Fault cleared at 0.2 seconds (fast dynamics)

* TSEMT terminated at 0.233 seconds

Bus 4 instantaneous voltages

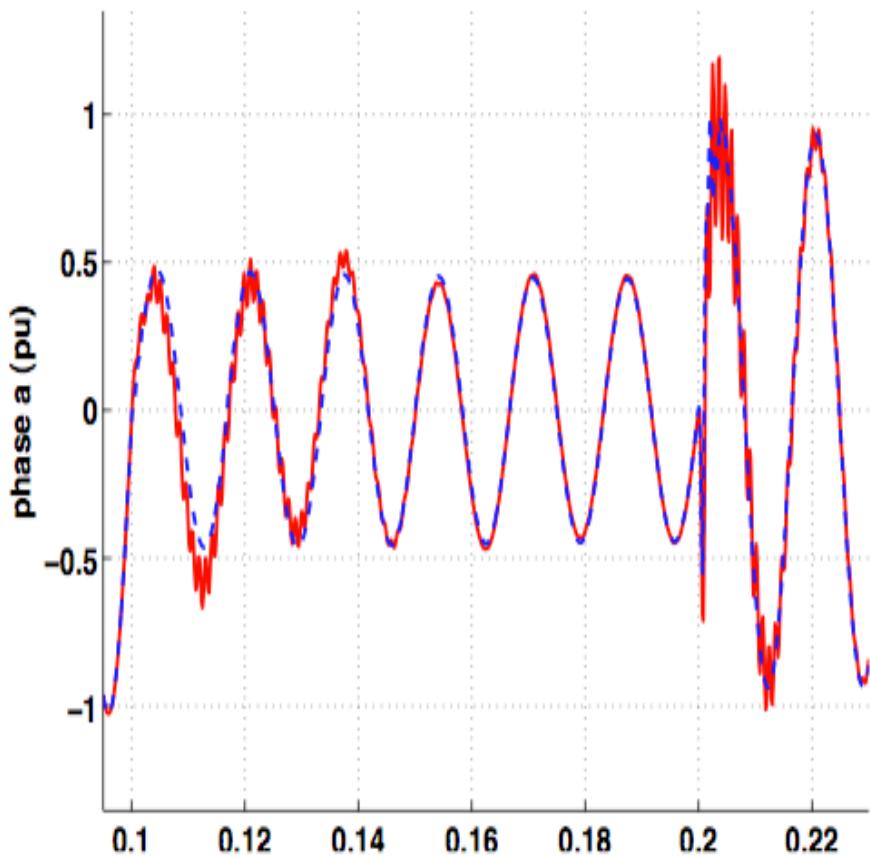


Boundary bus 4 instantaneous currents

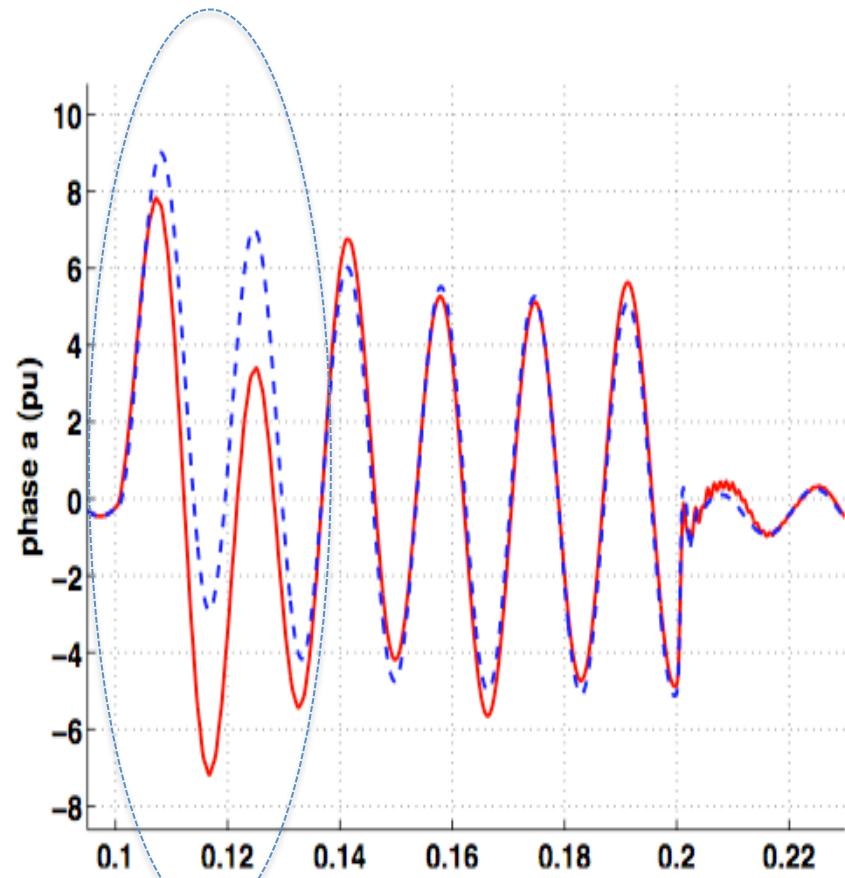


Zoomed-in fast dynamics

Bus 4 instantaneous voltages

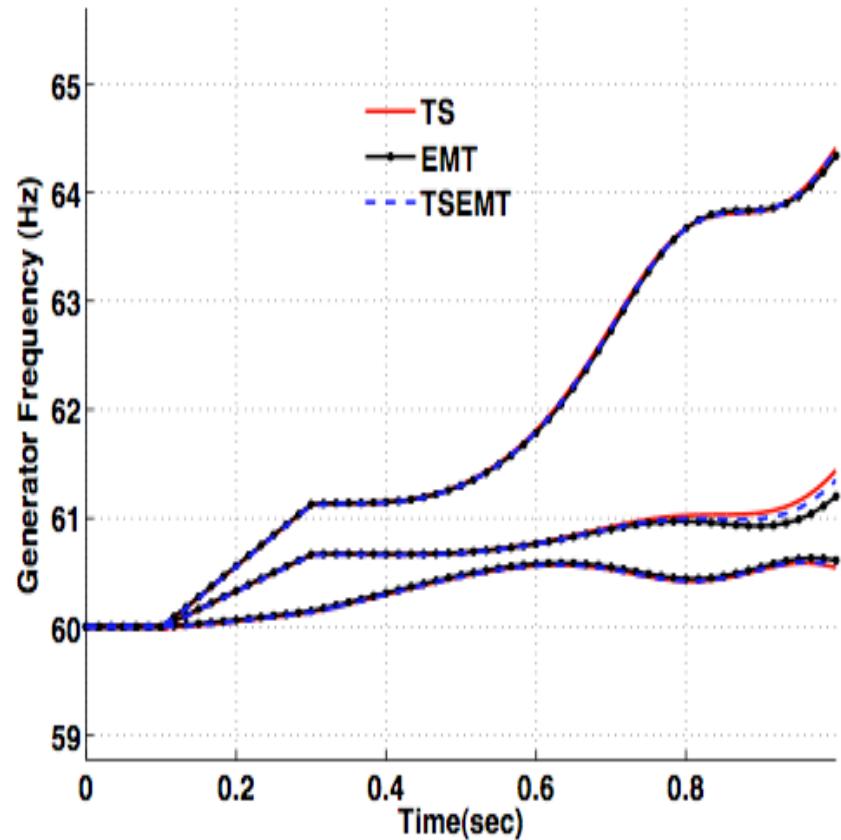


Boundary bus 4 instantaneous currents

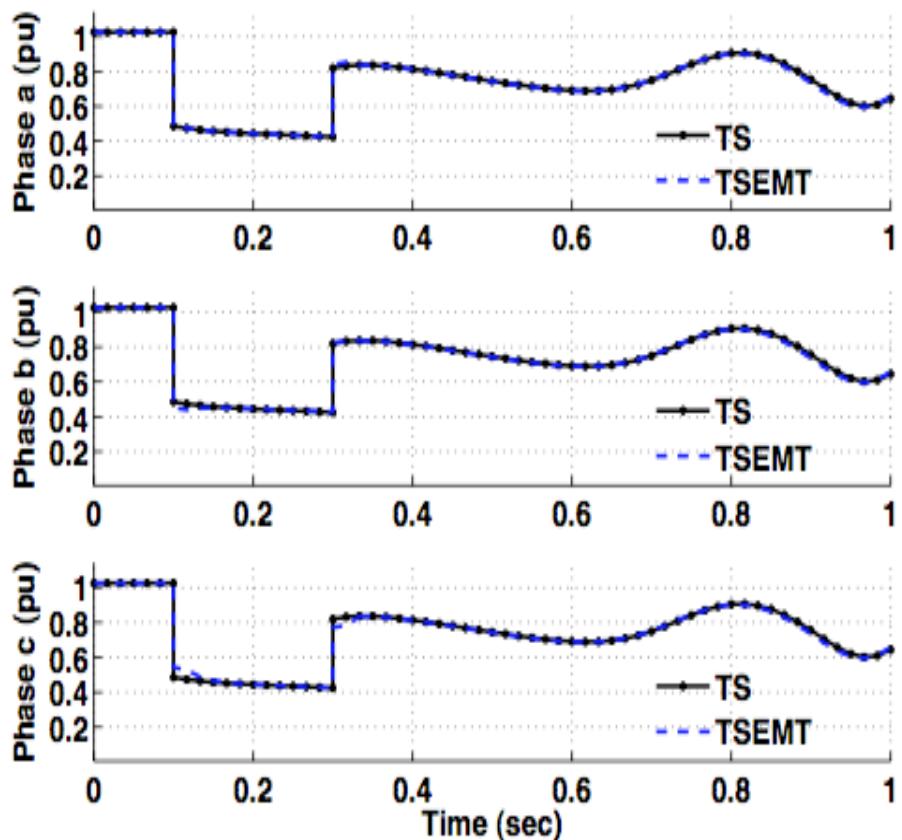


Fault cleared at 0.3 seconds (slow dynamics)

Generator frequencies



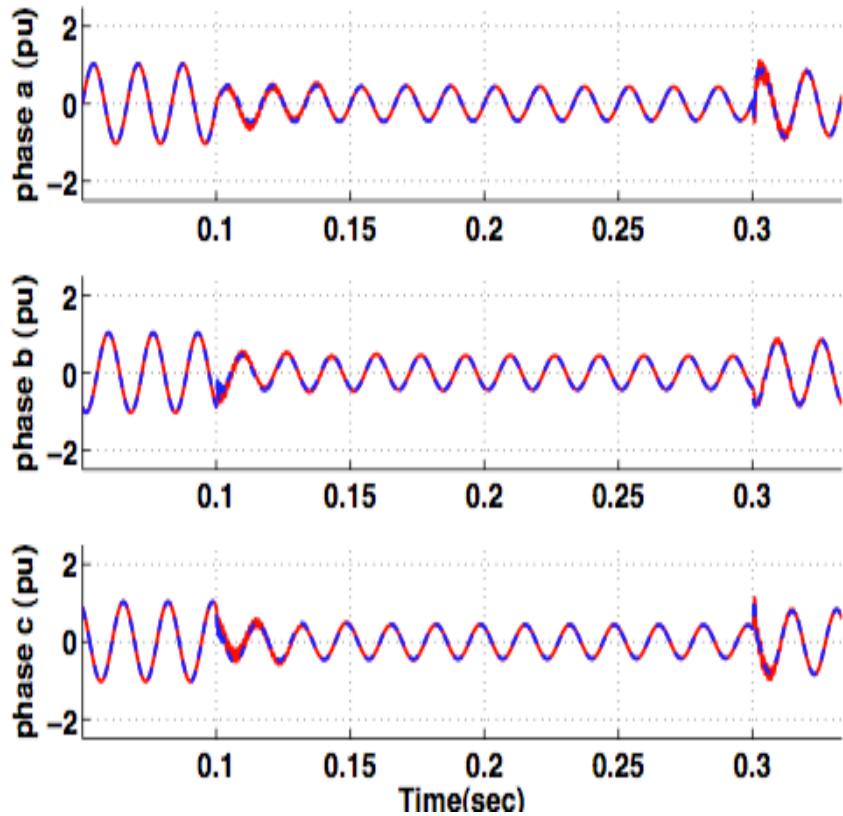
Bus 4 voltage magnitudes



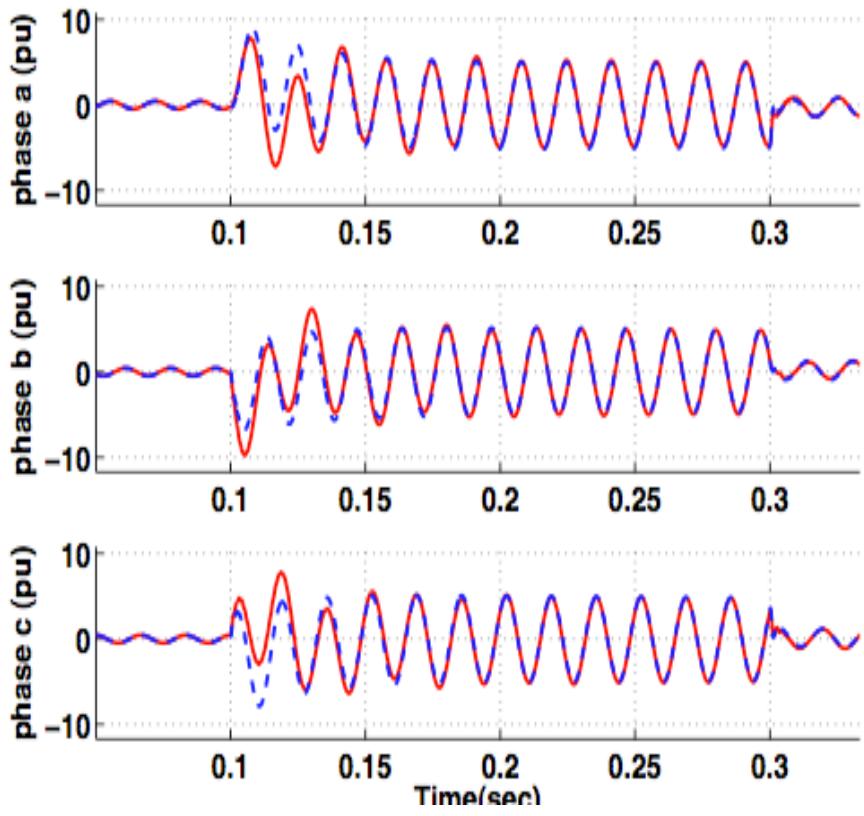
Fault cleared at 0.3 seconds (fast dynamics)

* TSEMT terminated at 0.233 seconds

Bus 4 instantaneous voltages

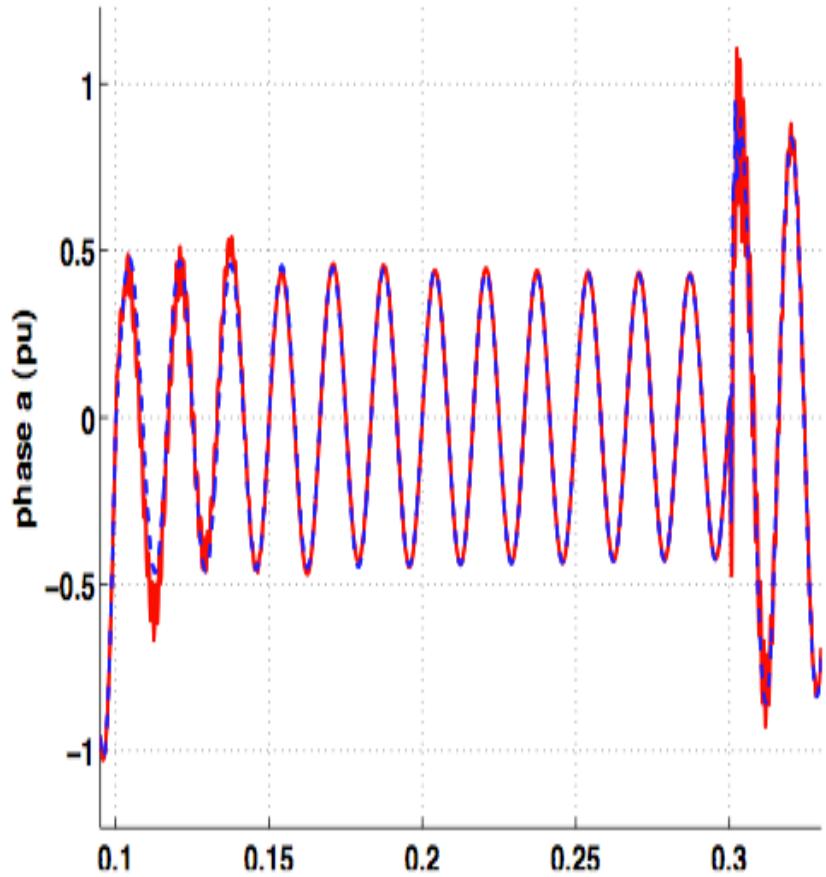


Boundary bus 4 instantaneous currents

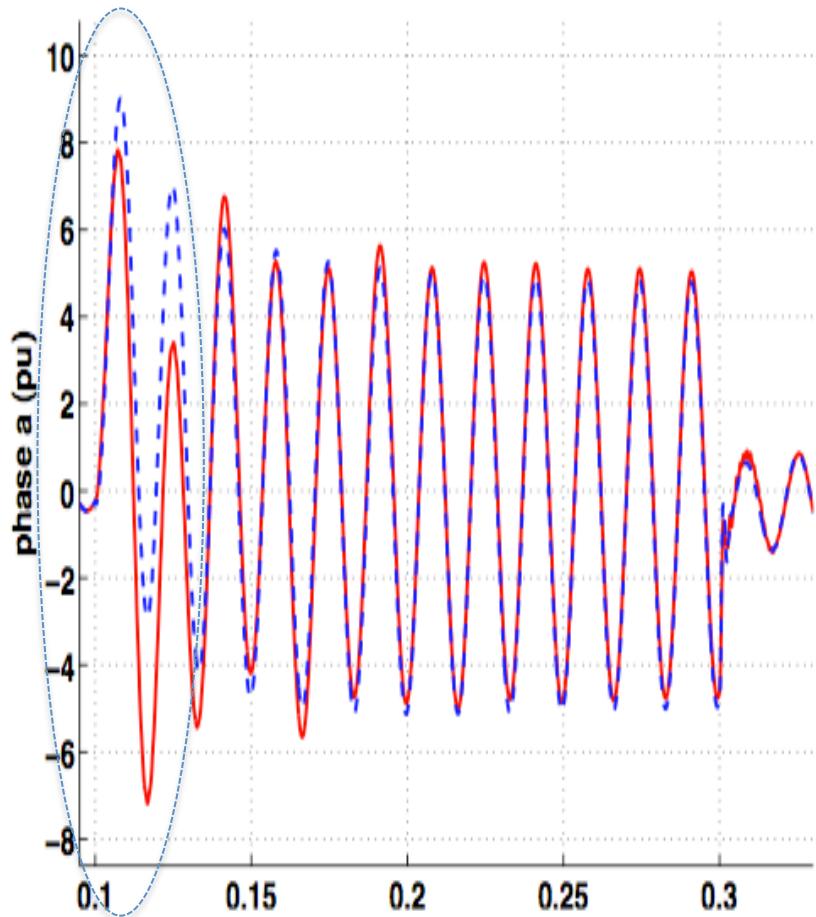


Zoomed-in fast dynamics

Bus 4 instantaneous voltages



Boundary bus 4 instantaneous currents

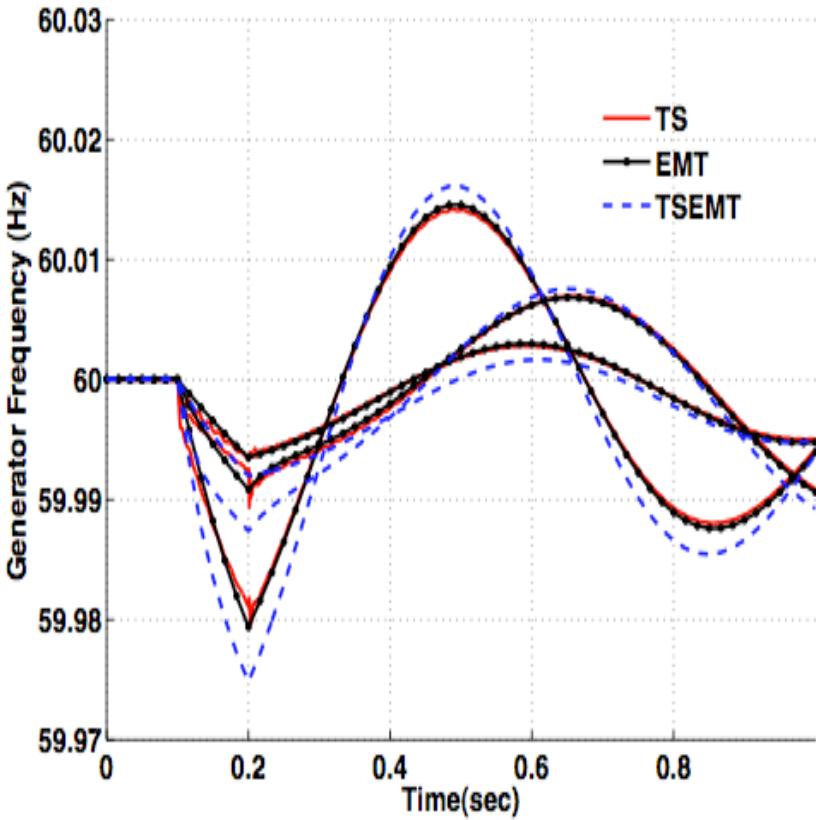


118-bus system test case

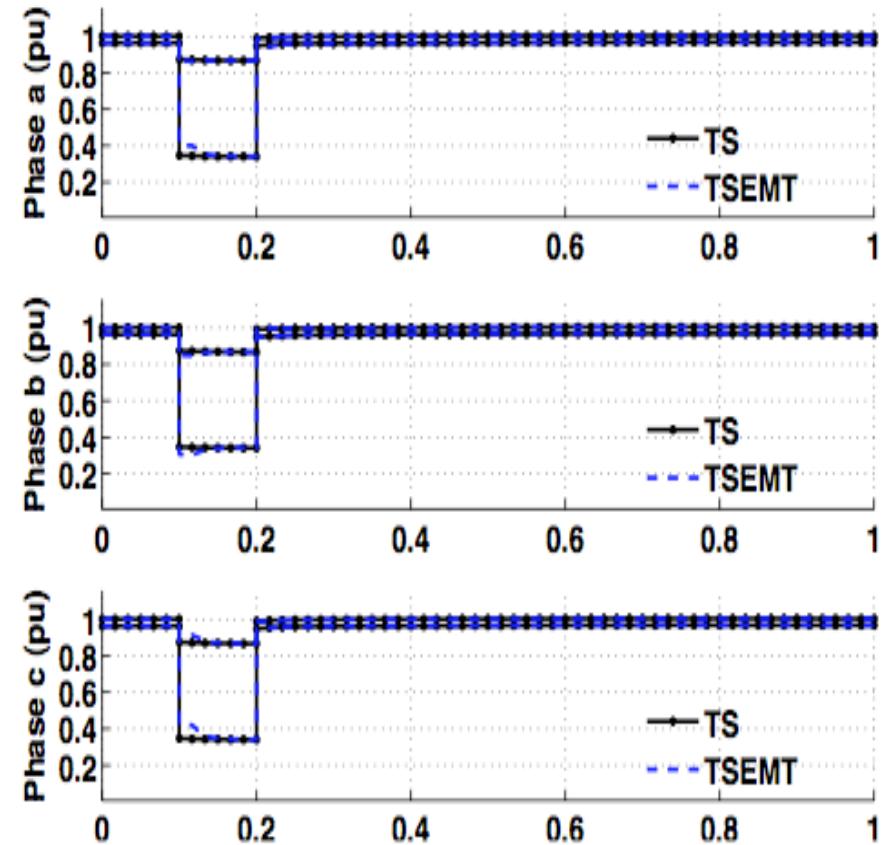
- 118 buses, 186 branches.
- Detailed system formed by radial section formed by buses 20, 21, 22, and 23.
- Detailed system has 3 transmission lines, 4 loads.
- Buses 20 and 23 form the boundary buses.
- Three phase fault applied at 0.1 seconds and removed at 0.2 seconds.

118 bus system (External system slow dynamics)

- Frequencies for three generators closest to the detailed system

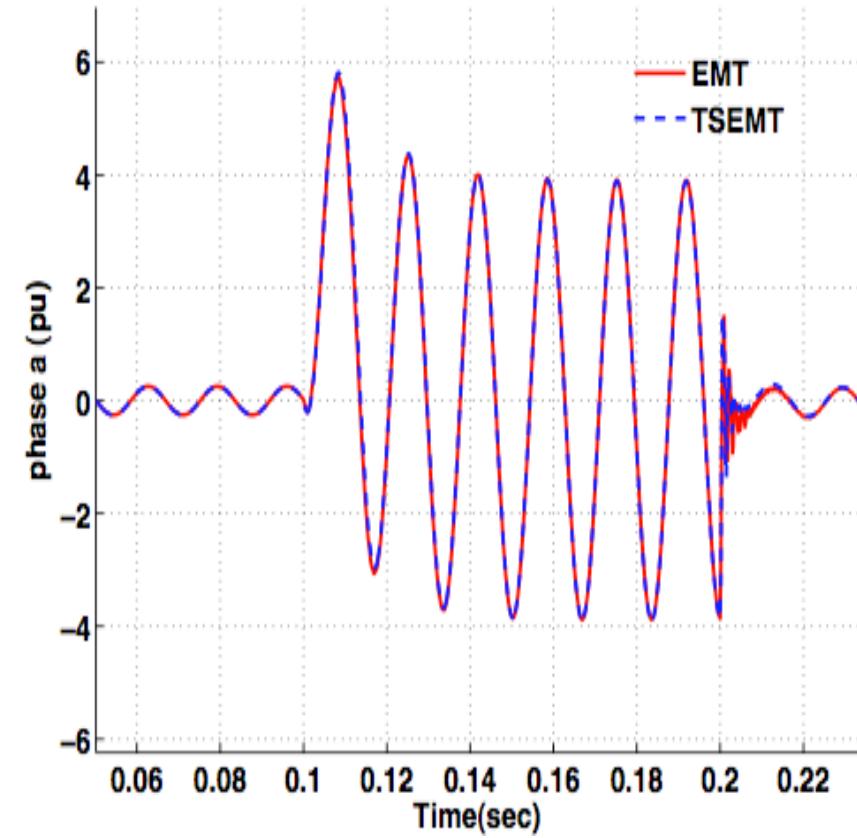
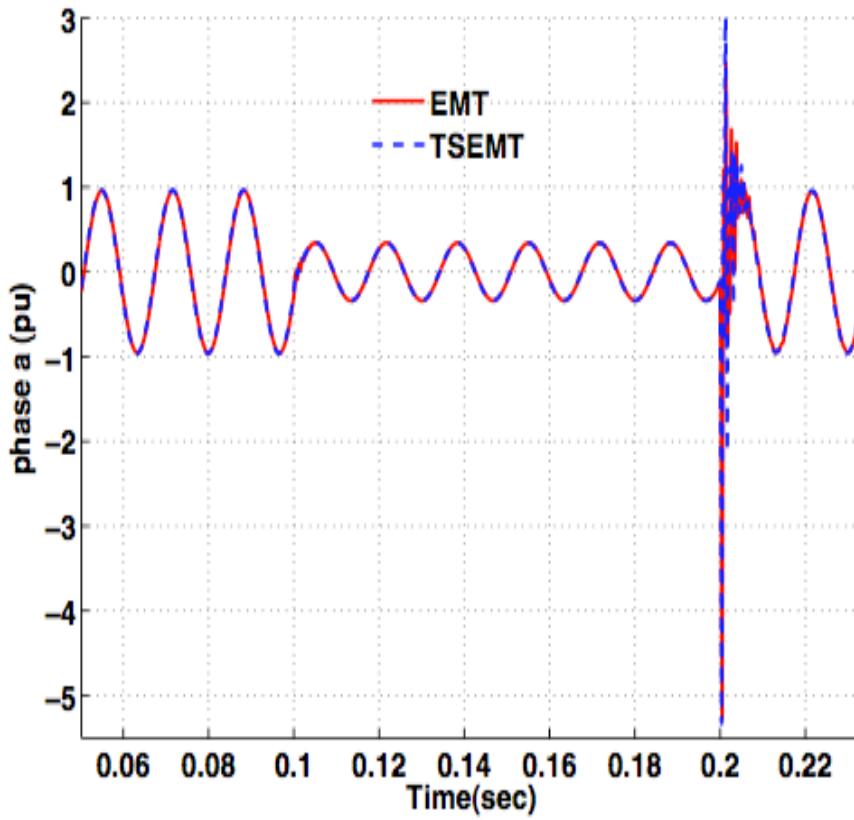


- Boundary bus 20 and 23 voltage magnitudes



118 bus system (detailed system fast dynamics)

- Bus 20 phase a instantaneous voltage
- Bus 20 phase a boundary current



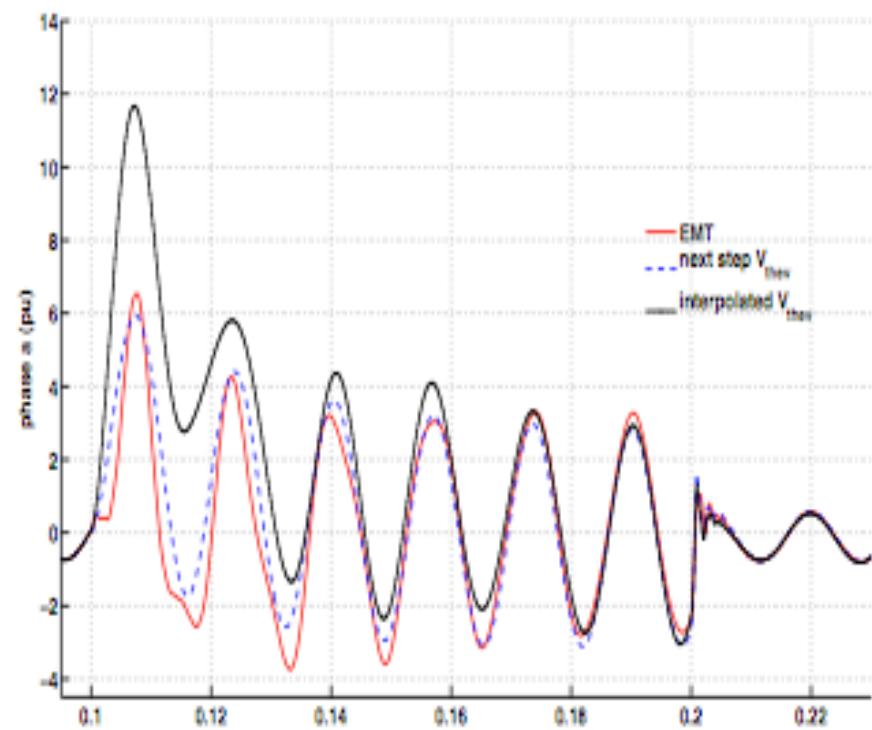
Network equivalents (External system equivalent for EMT)

- Additional equation for EMT

$$L_{thev} \frac{di_{bdry}}{dt} = v_{thev} - R_{thev} i_{bdry} - v_{bdry}$$

- Need to compute instantaneous $v_{thev}(t)$ from phasor V_{thev} available at only at each TS time step.
- Possible choices
 - Use V_{thev} from previous time step (existing hybrid simulators)
 - Use an interpolated value.
 - Use next step V_{thev}

- Using next step V_{thev} was found to be better.



[X_TS]